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RESEARCH ARTICLE

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Impact of ocean–atmosphere coupling on future projection of Medicanes in the Mediterranean sea

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Abstract

Cyclones with tropical characteristics called medicanes ("Mediterranean Hurricanes") eventually develop in the Mediterranean Sea. They have large harmful potential and a correct simulation of their evolution in climate projections is important for an adequate adaptation to climate change. Different studies suggest that ocean–atmosphere coupled models provide a better representation of medicanes, especially in terms of intensity and frequency. In this work, we use the regionally-coupled model ROM to study how air-sea interactions affect the evolution of medicanes in future climate projections. We find that under the RCP8.5 scenario our climate simulations show an overall frequency decrease which is more pronounced in the coupled than in the uncoupled configuration, whereas the intensity displays a different behaviour depending on the coupling. In the coupled run, the relative frequency of higher-intensity medicanes increases, but this is not found in the uncoupled simulation. Also, this study indicates that the coupled model simulates better the summer minimum in the occurrence of medicanes, avoiding the reproduction of unrealistically intense events that can be found in summer in the uncoupled model.

KEYWORDS

air-sea coupling, climate change, Medicanes, regional climate model, tropical-like cyclones

1 | INTRODUCTION

The Mediterranean basin is one of the main cyclogenetic regions in the world (Alpert and Neeman, 2016). This is likely due to the orographic conditions, as well as the thermodynamic characteristics found over the Mediterranean sea (Trigo *et al*., 2002). Among the large amount of cyclones that develop in this area, cyclones with tropical characteristics - often referred to as medicanes (MEDIterranean hurriCANES; Cavicchia *et al*., 2014a)—have lately attracted special attention from the scientific community due to its large harmful potential, especially in coastal regions. In recent years, there have been some instances of intense medicanes. For example, the one that occurred in November 2011 (Miglietta *et al*., 2013; Dafis *et al*., 2018) affecting coastal regions of the Western Mediterranean, or the medicane Zorbas in September 2018, which caused heavy rains and strong winds in zones of Greece.

Although medicanes do not develop frequently, they are associated with extreme weather phenomena (Cavicchia *et al*., 2014a). Medicanes present some similarities with tropical cyclones and tend to have a circular cloud pattern, often with an eye-like feature (Claud *et al*., 2010). Medicanes are typically a few hundred kilometres wide, while tropical cyclones can exceed 1,000 km in diameter (Zhang *et al*., 1998). These storms are more frequent during autumn and winter, and are practically non-existent in summer (Cavicchia *et al*., 2014a). Medicanes are usually associated with strong winds, heavy precipitations and enhanced oceanic waves (Mazza *et al*., 2017).

A few decades ago, medicane detection was only possible through the use of satellite images and radar (Reed *et al*., 2001; Fita *et al*., 2007). Nowadays, thanks to advances in computing power and improvements in model formulation, they can be identified in high resolution weather prediction models. Moreover, climate simulation of medicanes became possible with the development of regional climate models which downscale reanalysis data or global climate models. Although their low horizontal resolution (i.e., 50 km) was initially insufficient to properly identify medicanes due to their small size (Giorgi and Lionello, 2008), the recent introduction of high-resolution regional models led to a considerable improvement in medicane detection because they are able to simulate mesoscale cyclones (Romera *et al*., 2017; Gaertner *et al*., 2018) with resolutions that in some cases are close to 10 km.

Until recently, the impact of atmosphere–ocean coupling has been analysed using global models with low resolution both in the atmosphere and in the ocean (Bristol *et al*., 2017). However, in regional scales, for the representation of many key oceanic and atmospheric processes, higher horizontal resolution in the atmosphere and ocean is a priority (i.e., Haarsma *et al*., 2016; Hewitt *et al*., 2017). Increasing ocean model resolution has a key impact on the representation of the role eddies play in the ocean heat budget and, in turn, in the climate system (Griffies *et al*., 2015). In the extratropical atmosphere, in the large scale, increased surface wind stresses lower the sea-surface temperature (SST) through increased turbulent fluxes out of the ocean (Frankignoul, 1985) but, in a smaller scale, the relationship can be of opposite sign: a warmer SST leads to an increased surface wind stress (Small *et al*., 2008). Impacts are also seen in coupled atmosphere–ocean models, provided they have an ocean resolution of 1/4° or finer (Roberts *et al*., 2016). Although the increase of computational resources has allowed coupled Earth System Models to achieve a greater horizontal resolution, they are still run with relatively low resolutions in long-term climate simulations. This, together with the necessary parameterisations of subgrid-scale processes does not allow GCMs to capture some key physical phenomena and hampers the accuracy of climate projections on regional and local scales. This is especially true in the Mediterranean region, where high resolution is necessary for both the oceanic and atmospheric components (Xie *et al*., 2015).

Downscaled climate projections performed with uncoupled regional atmospheric models indicate a rise in intensity and a decrease in frequency of medicanes by the end of this century (Gaertner *et al*., 2007; Cavicchia *et al*., 2014b). Some studies on medicanes have been performed with coupled models during the last years, but using models with limited coupling and horizontal resolution, or without addressing the changes of medicanes in the future climate. In the analysis performed by González-Alemán *et al*. (2019), the authors use a global coupled model with high-resolution in the atmosphere (i.e., 25 km), but a coarser resolution for the oceanic component (i.e., 100 km). Furthermore, in that study air-sea coupling is partial. The climatological analysis by Gaertner *et al*. (2018) of the role of air-sea coupling and horizontal resolution is limited to present-day medicanes, like in the study of Akhtar *et al*. (2014), in which a high-resolution atmospheric model is coupled to a simplified one-dimensional ocean model.

The main novelty of the present work is the analysis of future projections of medicanes under anthropogenic climate change, using a fully-coupled regional climate model with high horizontal resolution in both the atmosphere (25 km grid spacing) and the ocean (between 5 and 10 km grid spacing). We use the regionally-coupled model ROM, which is composed of the regional atmospheric model REMO and the global ocean-sea ice model MPIOM. ROM has been previously used to address the oceanography and climatology of different regions of the world, including the Mediterranean (e.g., Cabos *et al.*, 2017; Parras-Berrocal *et al.*, 2020). For the analysis of the impact of coupling on the changes in frequency and intensity of the medicanes in the future under the RCP8.5 scenario, we compare two ROM and REMO simulations that share the same configuration in the atmosphere and only differ by the coupling. Then, we propose some plausible hypotheses about the causes of the difference of these changes in the future. This paper is organized as follows: in Section 2 we present the configurations of ROM and REMO used in this study and the methodology used to detect medicanes. The decadal and monthly frequency and intensity of simulated medicanes are discussed in Section 3. Finally, the conclusions are presented in Section 4.

2 | METHODOLOGY

2.1 | Model setup and simulations

In this work, we use the regionally-coupled model ROM (Sein *et al.*, 2015) and its stand-alone atmospheric component REMO (Jacob *et al.*, 2001). ROM is composed of the global oceanic model MPIOM coupled to the regional atmospheric model REMO. It has a dynamical core based on the Europa-Model of the German Weather service (Majewski, 1991) and physical parameterisations from the global climate model ECHAM6 (Roeckner *et al.*, 1996, 2003). The REMO domain used in this study covers a relatively large area, including parts of the Pacific Ocean, the North Atlantic and the Mediterranean region (see Figure 1), with a constant horizontal resolution of 25 km and 27 vertical levels from surface up to 10 hPpa. The oceanic component of ROM is the global ocean–sea ice model MPIOM (Marsland *et al.*, 2002), which has a variable horizontal resolution in the Mediterranean Sea ranging from ~5 km in the Western Mediterranean to ~20 km in the Eastern Mediterranean. MPIOM has 40 vertical levels with thicknesses that increase with depth, from 16 m at the uppermost layer to 500 m at the seafloor.

ROM includes also a global hydrological discharge model (HD, Hagemann and Dümenil Gates, 2001) which computes river runoff with a resolution of 0.5° and is coupled to the atmospheric and ocean components. REMO and MPIOM are coupled via the OASIS3 coupler (Valcke *et al.*, 2003), with a coupling interval of 3 hr, which allows us to take into account the diurnal cycle. The ocean and the atmosphere are coupled in the region covered by the atmospheric domain. In the uncoupled domain, MPIOM is driven by prescribed atmospheric forcing provided by the global climate model MPI-ESM-LR (Giorgetta *et al.*, 2013), which has a horizontal resolution of 200 km. MPI-ESM-LR also provides lateral boundary conditions for REMO in both coupled and uncoupled setups and the SST forcing for standalone REMO. In this work, we assume the RCP8.5 emissions scenario.

As stated above, in the uncoupled simulation with REMO, the SST needed for lower boundary conditions over the ocean is taken from MPI-ESM-LR. Therefore, the main difference between the simulations performed with ROM and REMO is the effect of interactive air-sea coupling. Whilst ROM is able to simulate the existing air-sea feedbacks, in REMO the oceanic variables are prescribed and thus do not respond to changes in the atmospheric

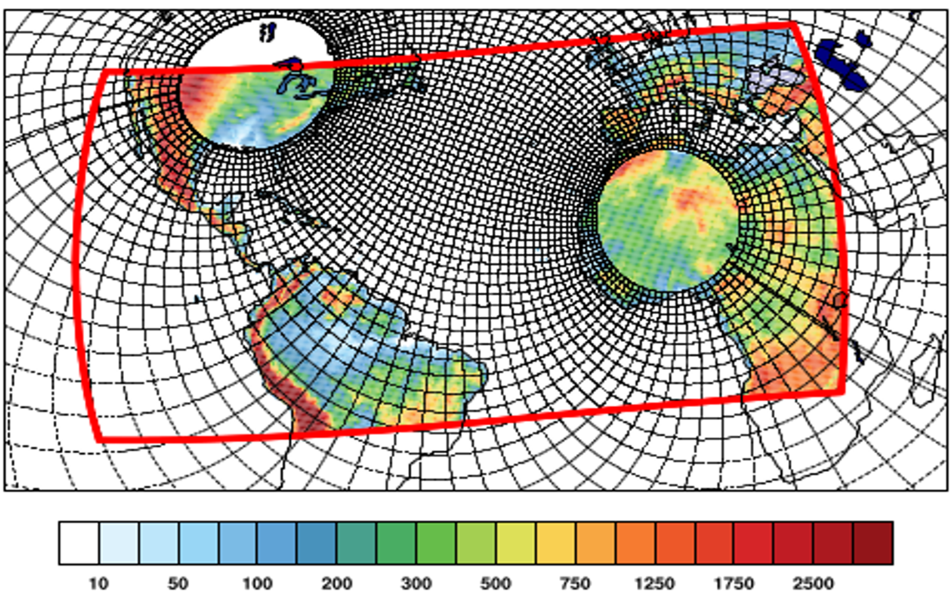

FIGURE 1 Domain boundaries of the regional atmospheric model REMO (thick red line), land orography (shading, in m) and grid of the global ocean model MPIOM (fine black lines; for clarity, only part of the grid lines are drawn). The uncoupled run only includes the atmospheric component that is delimited by the red line. While the coupled model covers the area of convergence between the atmospheric model (thick red line) and the oceanic model

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TABLE 1 Different runs used in this research

		Uncoupled simulation	Coupled simulation
Atmosphere	Atmospheric component	REMO	REMO
	Horizontal resolution	25 km	25 km
	Vertical resolution	27 levels to 10 hPa	27 levels to 10 hPa
Ocean	Oceanic component	—	MPIOM
	Horizontal resolution	—	5–10 km
	Vertical resolution	—	40 levels (10–500 m)
Atmosphere–ocean coupling		No	Yes

state. In ROM the air-sea fluxes are interactively calculated every coupled time step. This has a concomitant effect on the sea-surface temperature and sea-surface salinity which, in turn, determine the depth of the ocean mixed layer. Thus, we can assess the impact of air-sea interactions on medicane characteristics by comparing a coupled simulation with ROM and a stand-alone atmospheric simulation with REMO (see Table 1 for details). In our study, the simulations cover the 1951–2099 time period, which is divided into: past climate period (P1; 1951–2000), present/near future climate period (P2; 2001–2050) and future climate period (P3; 2051–2099). In the analysis, we have mainly used periods P1 and P3, as they allow to detect more clearly the effect of climate change on medicanes.

2.2 | Tracking and detection of medicanes

Medicanes are detected with the tracking method of Picornell *et al.* (2001), which is designed for mesoscale cyclones and therefore suitable for medicane detection. A wind speed filter is used to detect cyclones with at least tropical storm intensity, using a maximum 10 m-wind speed threshold of 17.5 ms^{-1} following the criterion of Walsh *et al.* (2007). Only cyclones that exceed the tropical storm threshold are considered.

After the tracking, the structure of the detected cyclones is examined. This allows us to exclusively consider those cyclones with tropical characteristics. To do so, we apply the cyclone phase space method (CPS; Hart, 2003). The CPS is an objective method to represent the 3-D structure of cyclones and classify them depending on their thermal structure. As a result of the small size of medicanes, it is necessary to apply the CPS criteria over a reduced radius of 150 km around the low-pressure centre. This method is based on three different parameters: B, VTU and VTL. The B parameter gives an indication of the cyclone symmetry. Following Hart (2003), we assume that values of the B parameter above 10 m indicate an asymmetric (frontal) cyclone, while values below this threshold correspond to a symmetric (non-frontal) cyclone. The upper troposphere thermal wind (VTU) and the lower troposphere thermal wind (VTL), derive from the geopotential field from 600 to 300 hPa and from 900 to 600 hPa, respectively. These parameters determine the existence of a warm core or cold core cyclone (Hart, 2003). Specifically, negative values of thermal wind indicate a cold core cyclone, whereas positive values indicate a warm core cyclone. In the case of the tropical cyclones, values of both VTU and VTL should be positive to show a full-troposphere warm core cyclone. Cyclones having tropical characteristics for at least one time step of the model output (6 hr) are classified as medicanes. Because medicanes always develop over the sea, a mask is additionally applied in order to rule out those cyclones that arise over land.

3 | RESULTS

3.1 | Evaluation of the historical runs

First, we present a brief evaluation of the most important aspects of the medicane climatology simulated by both configurations of the model. Based on medicane climatologies (Miglietta *et al.*, 2013; Cavicchia *et al.*, 2014a), an annual frequency of 1.57 medicanes has been estimated for past climate conditions (1950–2000). In good agreement with this, we find 1.60 and 1.82 medicanes per year in the coupled (ROM) and uncoupled runs (REMO), respectively (Table 2). We would like to point out that we also performed coupled and uncoupled simulations with a low-resolution configuration of the atmospheric component in REMO (50 km). However, these simulations clearly underestimated the observed yearly frequency of medicanes and reproduced less than one event per year. Therefore, we decided not to use these runs in this work.

For evaluating past trends of medicane frequency, we use the climatology of Cavicchia *et al.* (2014a) because it is the most complete climatology of medicanes available and it covers a long time period (1950–2010). We have performed an analysis of the annual frequency of medicanes for this time period, comparing the observed trend of the climatology of Cavicchia with the trends the coupled and uncoupled runs. Results (Figure 2a) indicate a subtle increasing trend of medicanes for the climatology of Cavicchia, while a slight declining trend is found for both the coupled and uncoupled runs. Nonetheless, all trends are not significant, and it should be taken into account that the simulations are nested in a global climate model, not in reanalysis, so that a very close coincidence should not be expected.

We have also compared the spatial distribution of the simulated medicanes with the distribution shown in Cavicchia *et al.* (2014a). The main area of observed medicane development in the Western Mediterranean is well captured in both simulations, while the observed secondary maximum of the Central Mediterranean is less clearly reproduced in the simulations (figure not shown).

Finally, regarding the quality of the SST simulated in the coupled run, there is a study from Parras-Berrocal *et al.* (2020), where the same configuration of ROM is used to investigate in detail the Mediterranean Sea, including the regional distribution of the SST and the

TABLE 2 Annual frequency of medicane frequency with the corresponding standard deviations for the different runs and the Cavicchia medicane climatology (Cavicchia *et al.*, 2014a)

Name	Annual frequency	*SD*
REMO	1.82	1.56
ROM	1.60	1.29
CAVICCHIA (climatology)	1.57	1.30

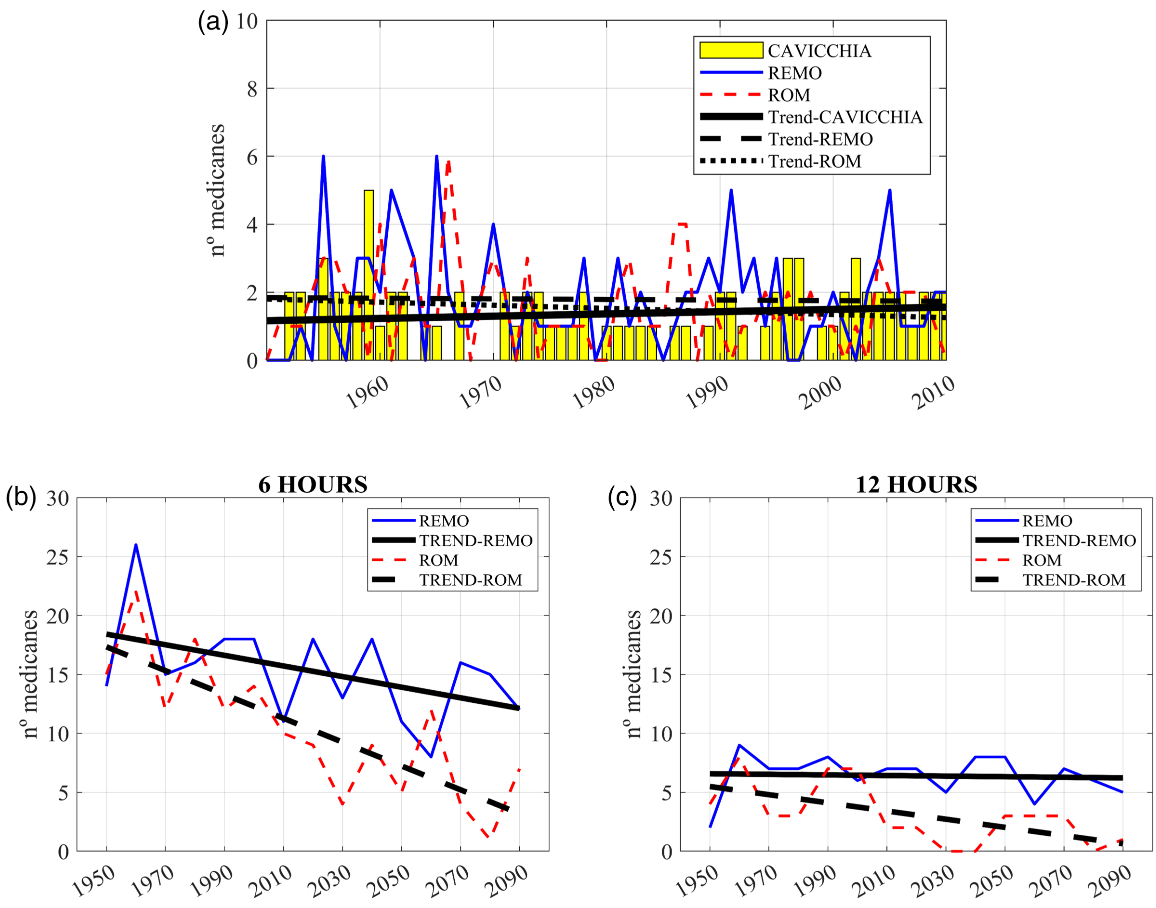

FIGURE 2 (a) Annual frequency of medicanes from Cavicchia climatology (Cavicchia et al. (2014); yellow bars), the uncoupled simulation (REMO; solid blue line) and coupled model (ROM; dashedred line) with its annual trends from 1951 to 2010. (b) Decadal frequency for the different runs until the end of the XXI century, assuming 6 hr as the minimum duration of the warm core criteria for selecting medicanes. The dashedred line shows the results from the coupled model (ROM) and the solid blue line those from the uncoupled model (REMO). The decadal frequency trend for the uncoupled and coupled runs in the last 150 years of the simulation time period (1950–2100) are shown with a solid black line and a dashed black line, respectively. (c) Same as (b), but establishing 12 hr as the minimum duration of the warm core criteria

SST trend. The validation performed in that study for the 1950–2000 period indicates that ROM has a performance similar to other state-of-the-art AOGCMs. These authors also perform an analysis of the SST trend o under the 8.5 RCP scenario. Their results show an increment of the SST of 2.7°C by the end of the XXI century in the Mediterranean basin. This trend is very close to the values obtained with the global earth system models MPI-ESM-LR and MPI-ESM-MR, which project respectively an increase of the SST of 2.8 and 2.9°C.

3.2 | Frequency

In this section, we first focus on the evolution of the decadal frequency of occurrence of medicanes. We focus on the changes in the trend of medicanes per decade in the future climate simulation for the different model configurations and the possible mechanisms that affect the decadal frequency under climatic change conditions. Lastly, we also study the monthly and seasonal frequency of medicanes.

3.2.1 | Decadal frequency of medicanes

Previous studies addressing the impact of climate change on medicanes have found a progressive decrease from 1951 until the end of the XXI century (e.g., Cavicchia *et al.*, 2014b; González-Alemán *et al.*, 2019). In line with this, the number of medicanes in our simulations decreases with time (Figure 2b). The significance of the linear trend has been calculated with a Student's t test. Results from the coupled run show a significant reduction of 1.01 (p-value $< .05$) medicanes per decade from 1951 to 2099, whereas a nonsignificant decrease of 0.45 (p-value $> .05$) medicanes per decade is found for the uncoupled run. These results highlight that air-sea coupling has a clear impact on the trend of the number of simulated medicanes

In (Figure 2c) we can see that the number of medicanes with a deep warm core duration of at least 12 hr is clearly smaller than in the standard case (at least 6 hr of warm core duration) both in ROM and REMO. We also note that the frequency of these medicanes remains almost constant in the uncoupled simulation, with a nonsignificant trend of −0.025 medicanes/decade (p-value $> .05$). In the coupled run, however, a significant trend of −0.35 medicanes/decade (p-value $< .05$) is found.

The consistent decline observed in the number of simulated medicanes towards the end of the XXI century could be explained by several mechanisms. On the one hand, this may be due to a reduction of the amount of extratropical/baroclinic precursors in the Mediterranean zone, as suggested in previous works (Ulbrich *et al.*, 2009; González-Alemán *et al.*, 2019). In our results, a statistically significant correlation between the decadal time-series of medicanes and extratropical cyclones (ECs) is found, which is stronger in the coupled (0.79; p value $< .05$) than in the uncoupled (0.56; p value $< .05$) run. This therefore implies that a reduction of the ECs will trigger a decrease in the number of simulated medicanes. The evolution of the number of both ECs and medicanes is presented in Figure 3a,b. In general, a decline in the number of ECs can be noticed (Zappa *et al.*, 2013), which is in agreement with the trend observed for medicanes. This decrease is more important in the coupled version, where there is also stronger correlation, as mentioned above, between ECs and medicanes. On the other hand, the future reduction in the number of medicanes may be triggered by an increase of the atmospheric stability over the Mediterranean Sea (Giorgi and Lionello, 2008). Cavicchia *et al.* (2014a) propose an "instability index" which is computed as the difference between the temperature at 350 hPa and the sea-surface temperature (SST). The authors find that values of this index below −58°C represent a favourable environment for medicane development. To quantify future variations of atmospheric instability, we first calculate this index for the past (P1; 1951–2000) and future (P3; 2051–2099) time periods for the coupled and uncoupled simulations. Then, for each configuration, we compute the differences between the historical and future indexes (Figure 3c,d). In these figures, negative values prevail (comparing absolute values of the index). This indicates that this index becomes smaller (in absolute value) and thus that the environmental conditions are less prone to medicane generation. Therefore, both the decrease in the number of extratropical cyclones in the Mediterranean Sea and the increase of atmospheric stability conditions are contributing to the decreasing trend of medicanes

3.2.2 | Monthly frequency

In previous works, it has been found that medicanes and ECs which affect Europe and the Mediterranean region have a similar monthly distribution (Lionello *et al.*, 2008). In general, the monthly frequency is maximum in winter and minimum in summer. In Figure 4a we show the monthly frequency for our set of simulations and the observed climatology (Cavicchia *et al.*, 2014b). It is relevant to highlight that both coupled and uncoupled configurations capture well the main aspects of the

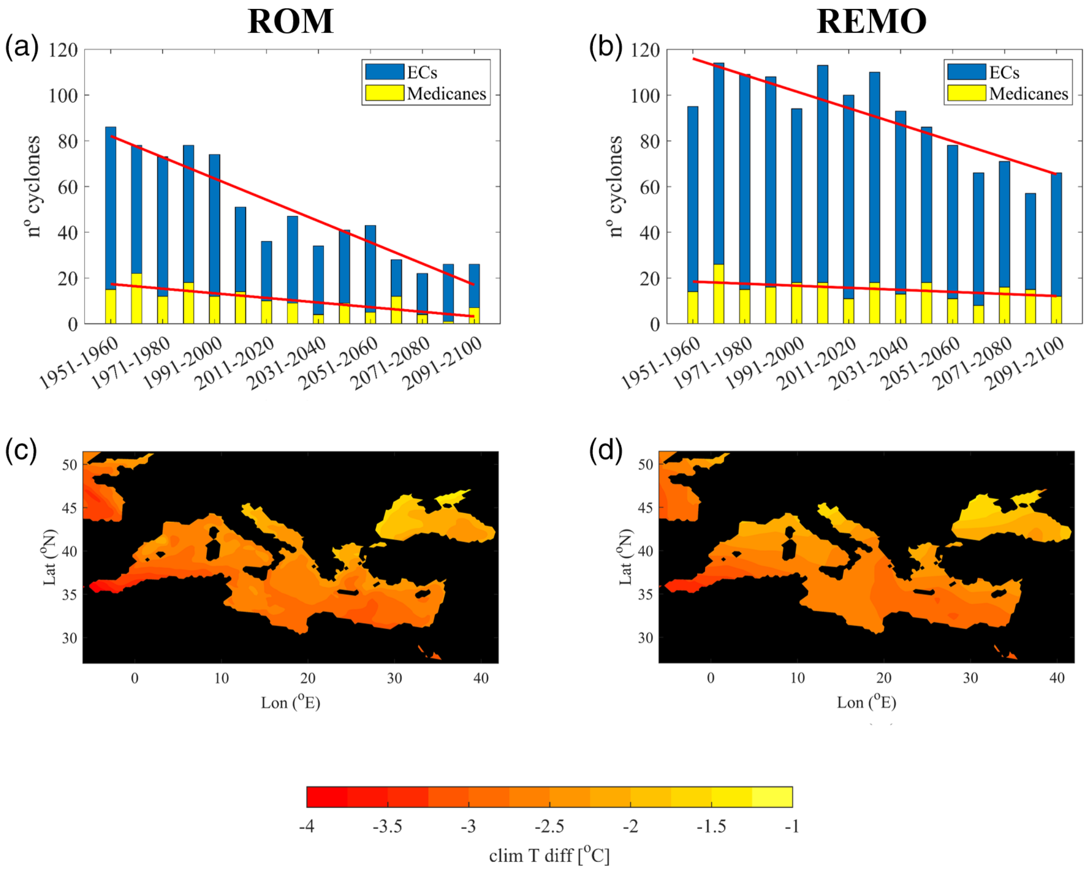

FIGURE 3 (a) Decadal frequency of medicanes (yellow bars) and extratropical cyclones (ECs; blue bars), as well as their trend over the simulation period (1951–2099; red lines) for the coupled model (ROM). (b) Same as (a), but for the uncoupled model (REMO). (c) Change of the instability index (°C) in the Mediterranean region between past (1951–2000) and future climate (2051–2099) for the coupled model (ROM). (d) Same (c), but for the uncoupled simulation (REMO)

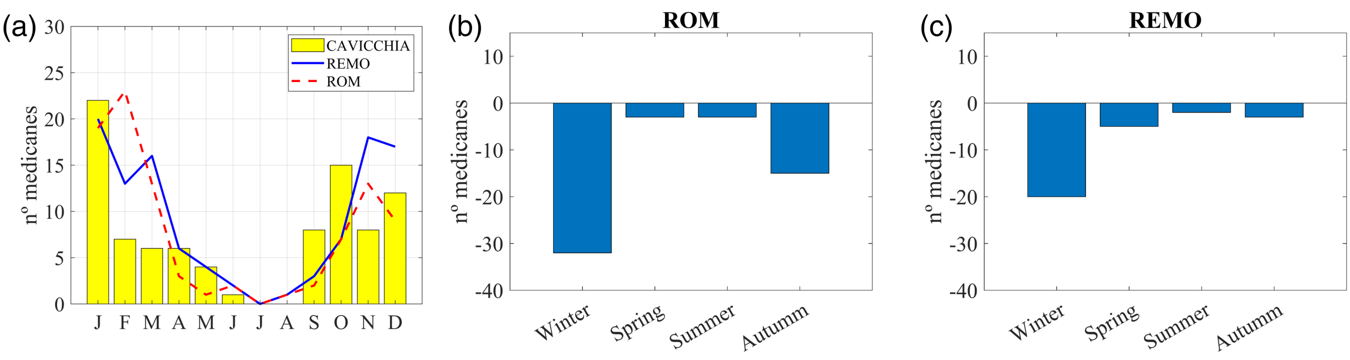

FIGURE 4 (a) Monthly frequency of medicanes in past climate (P1; 1951–2000) for the coupled run (ROM; dashed red line), the uncoupled run (REMO; solid blue line) and the climatology from Cavicchia *et al*., 2014b (yellow bars). (b) Variation of total number of medicanes per season between past (P1; 1951–2000) and future (P3; 2051–2099) climates for the coupled run (ROM). (c) Same as (b), but for the uncoupled run (REMO)

observed seasonal cycle particularly the summer minimum.

The seasonal variation in the number of medicanes in the future relative to the past climate is presented in Figure 4b for the uncoupled simulation and in Figure 4c for the coupled one. Results show a reduction of medicanes for both simulations in all seasons. The reduction is more pronounced in winter months. It is interesting to note that winter and autumn changes in ROM are clearly larger than in REMO.

To assess the significance of the changes in the number of medicanes per season in the future we use the Student's *t* test. We find that the number of medicanes in winter will be significantly lower than in past climate for both model configurations (*p*-value < .05). The main differences between runs appear in autumn. ROM shows an important decrease of the number of medicanes in 50 years (15 medicanes; *p*-value < .1), while REMO shows a much smaller reduction which is not statistically significant (3 medicanes; *p*-value > .1).

3.3 | Medicane intensity

In this section we address the study of medicane intensity taking into consideration the following variables: VTU (the parameter from the cyclone phase space method indicating the cold/warm core character of the cyclone in the upper troposphere) and the maximum wind speed (representative of the medicane intensity). The correlation between the maximum wind speed and VTU is also examined to detect the possible relationship between intensity and tropical characteristics in medicanes.

3.3.1 | Maximum wind speed

As stated above, in Cavicchia *et al.* (2014b) the authors make use of reanalysis data to investigate the past-day climate distribution of maximum wind speed within the cyclonic region. Following that study, we perform a similar analysis but taking into consideration winds from the two model setups considered (Figure 5a).

The differences between the coupled and uncoupled simulations indicate that the wind speed distribution for the coupled run is displaced towards lower wind speed values in comparison to the uncoupled run. For the higher intensity values, the uncoupled run shows higher

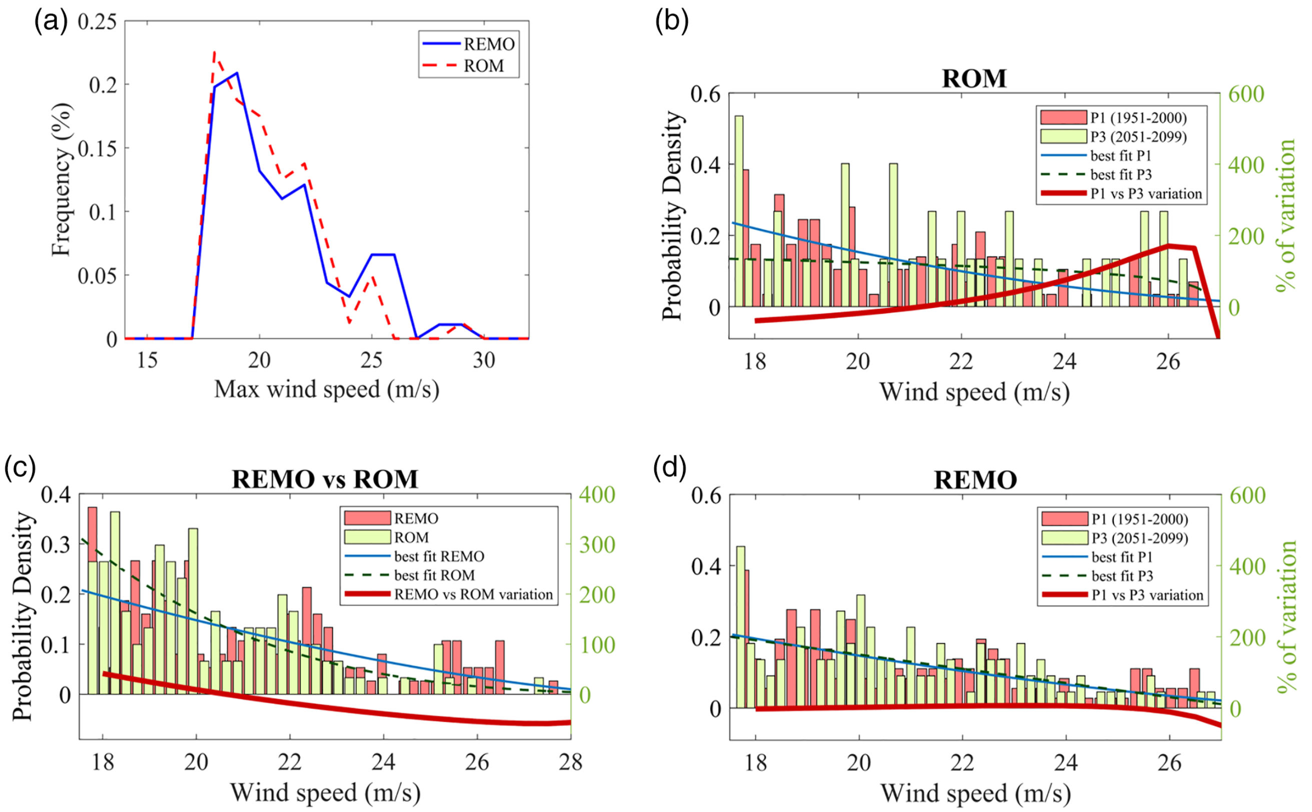

FIGURE 5 (a) Distribution of maximum wind speed per cyclone in past climate (period 1, P1: 1951–2000) for the uncoupled model (REMO; solid blue line) and the coupled model (ROM; dashed red line). (b) Values of maximum wind speed in medicanes for present climate (P1; red bars) and future climate (period 3, P3: 2051–2099; green bars), probability density function (pdf) of maximum wind speed for past climate (best fit for P1; solid blue line) and future climate (best fit for P3; dashed green line), for the coupled model (ROM). The thick redcurve shows the percentage variation of the pdf for P3 with respect to the pdf for P1. (c) Same type of graph as b), but comparing the coupled model (ROM) to the uncoupled model (REMO). (d) Same as (b) but for the uncoupled model (REMO)

frequency of medicanes than the coupled run (Figure 5c). To determine the statistical significance of these differences we perform a Wilcoxon rank sum test (Wilks, 2006). This statistic is used to assess whether the two wind distributions are different with a confidence interval of 95%. We find that results obtained from the two simulations are significantly different (p-value = .021). This allows us to conclude that wind intensity of medicanes simulated in the coupled and uncoupled runs is different.

The simulated maximum wind speeds in our models are smaller wind than in the 10-km resolution climatology (not shown; see Cavicchia *et al.*, 2014b). This may be because the atmospheric resolution considered in this study (25 km) is still insufficient to allow for a correct representation of the maximum wind speed in mesoscale cyclones. This is an indication that the use of atmospheric models with a greater horizontal resolution is required to further improve the representation of mesoscale cyclones.

Future changes in medicane intensity are examined through the analysis of the probability density function for the maximum wind speed in the coupled (Figure 5b) and the uncoupled (Figure 5d) runs. Specifically, these figures show the distribution function of wind speed and its associated variation between past (P1 in Figure 5b,c; 1951–2000) and future (P3 in Figure 5b,c; 2051–2099) climates. In the coupled run, the frequency of high wind speeds (above 22 m/s) increases, whereas almost no change in wind speed frequency is found in the uncoupled run. The future decline in frequency found for the highest wind speeds (above 27 m/s) in the coupled run might just be an artefact of the very low number of medicanes simulated with these wind speeds.

3.3.2 | Tropical structure analysis

As mentioned above, positive values of VTU indicate an upper-troposphere warm core cyclone (which is typically associated with a deep warm core cyclone), while negative values correspond to an upper-troposphere cold core cyclone. High values of VTU indicate that the cyclone has strong tropical characteristics.

The work of González-Alemán *et al.* (2019) shows that the values of VTU and the maximum wind speed are correlated for medicanes. Therefore, medicanes with a more intense warm core will have typically a greater maximum wind speed. An explanation for this association is that the more intense warm core implies stronger convection and thus a larger release of latent heating which, in turns, leads to a higher radial pressure gradient, thus increasing wind speed. Such a link has been found more generally in the case of tropical cyclones, for example, by Jiang (2012).

The correlation analysis for past climate medicanes reveals a statistically significant (p-value < .05) relationship between the maximum wind speed and VTU both in the uncoupled (r = .204) and the coupled (r = .282) simulations. However, the results obtained for future climate are different for each model. The coupled model shows higher values of both maximum wind speed and VTU in the future. At the same time, the correlation between maximum wind speed and VTU is also greater in the future (r = .435; p-value < .05). In contrast to this, the uncoupled model shows a future decrease of both the maximum wind and the values of VTU parameter. No statistically significant correlation (r = −.008; p-value > .05) is found in this latter case between the maximum wind and the warm core intensity. This contrasting behaviour suggests a clearer relationship between intensity and tropical characteristics in the future, which is consistent with the findings of González-Alemán *et al.* (2019).

3.4 | Seasonal dependence of the effects of coupling

In order to assess whether the effects of coupling are seasonally dependent, we make a seasonal comparison of the duration of the medicanes (measured by the number of 6 hr time steps) and the intensity distribution between the coupled and uncoupled simulations (Figure 6). As the number of medicanes for some seasons is very low, in order to have a reasonable sample of medicanes, we take into account the whole simulation period (1951–2099) for both model configurations.

We note that the largest differences in medicane intensity between the coupled and uncoupled simulations take place in summer (Figure 6g). Almost no summer medicanes are simulated by the coupled model, and the intensity of the few cases is clearly lower than that of the uncoupled model. An examination of individual cyclone cases indicates that in the uncoupled simulation, cases of long-lasting summer cyclones associated with high wind speeds are found, which does not occur in the coupled run. Observations and reanalysis-based studies indicate, in good agreement with the coupled simulation, that medicanes are very infrequent in summer (e.g., Miglietta *et al.*, 2013; Cavicchia et al., 2014a).

A likely explanation for the occurrence of unrealistic intense summer medicanes in the uncoupled simulation is that in this model configuration the SST does not undergo changes due to the action of the strong winds of the cyclone since the SSTs are prescribed. In contrast to

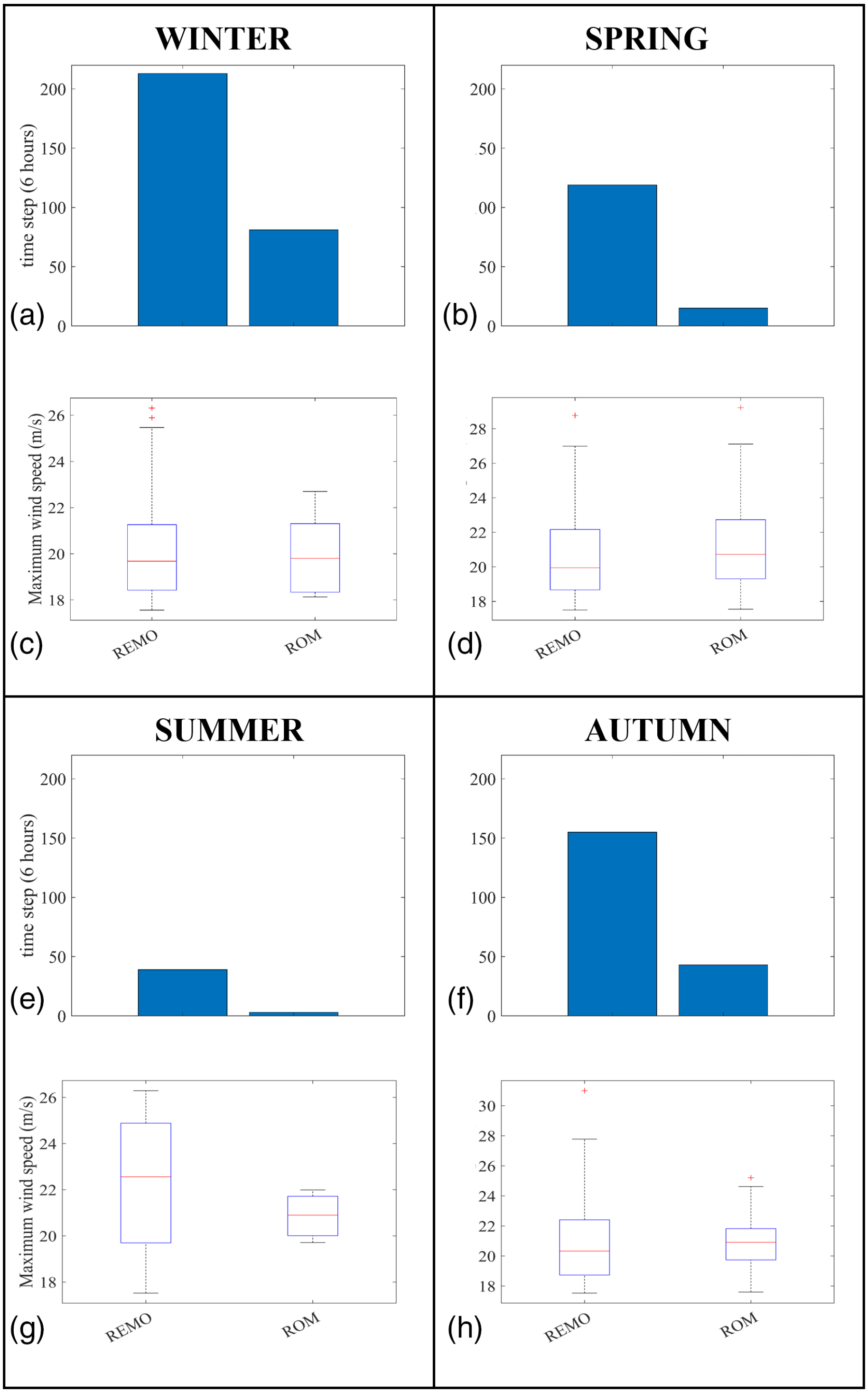

FIGURE 6 (a) Accumulated number of cyclone time steps in winter, considering the entire time period studied (1950–2100). (b), (e) and (f): as (a), but for spring, summer and autumn, respectively. (c) Boxplots of maximum wind speed for each time step for the whole study period (1951–2099) in winter. (d), (g), (h): as (c) but for spring, summer and autumn, respectively

this, in the coupled run the SSTs can vary in response to atmospheric forcing. We hypothesize that in the coupled run, due to air-sea coupling the ocean would respond to any intensifying atmospheric disturbance in their initial phase, through an SST reduction due to upwelling of colder water from below the mixed layer caused by the accelerating winds. Decreasing SSTs would limit a further development of the medicane. The mixed layer in summer over the Mediterranean Sea is very shallow, which would facilitate this negative feedback. But due precisely to the lack of intense summer medicanes in the coupled simulation, this explanation cannot be verified directly. The mixing effect induced by intense winds can only be assessed through proxies, like strong wind situations that are unrelated to cyclones. In the work from Berthou *et al.* (2016) the authors find a strong decrease of the SST (about 3°C) in the Western Mediterranean after an extreme Tramontane event in September. This shows the cooling potential of strong winds over shallow mixed layer waters in the Mediterranean.

4 | CONCLUDING REMARKS

In this paper, we have examined the influence of air-sea coupling on future projections of medicanes. To that end, we run a set of coupled and uncoupled simulations with the regionally-coupled climate model ROM and its atmospheric stand-alone model REMO. In ROM, the global ocean model MPIOM is regionally coupled to the limited-area atmospheric model REMO. This allows us to have air-sea interactions at a rather high resolution in the area of interest at an acceptable computational cost. Our results highlight the importance of the use of high-resolution coupled models to represent mesoscale cyclones like the medicanes.

The frequency of present time medicanes in the coupled model is closer to that obtained from downscaling of reanalysis data (Cavicchia *et al*., 2014a) than the frequency for the uncoupled model. In future climate, the frequency of medicanes experiences a significant decrease which is more pronounced in the coupled configuration. Our interpretation is that this decline may be due to: (a) a reduction in the number of extratropical cyclones (ECs) and (b) an increase of atmospheric stability, which is unfavourable for medicane generation. This is in agreement with several works in which a significant lowering of ECs and increased stability conditions (Giorgi and Lionello, 2008; Ulbrich *et al*., 2009; Romera *et al*., 2017) have been found in future climate projections.

The two runs reproduce quite well the main aspects of the monthly cycle of medicanes inferred from downscaled reanalysis data (Cavicchia et al., 2013). In future climate, a reduction of the number of medicanes per season is obtained. This reduction is more pronounced in winter in the coupled model (30 medicanes in 50 years). There are also differences in the projected change in autumn between the coupled (15 medicanes in 50 years) and the uncoupled simulations (3 medicanes in 50 years).

Previous works about the impact of climate change on medicanes, show an intensity increase of medicanes in the future. Our results show the response of the intensity depends on the coupling. In the coupled version there is an increase in the relative frequency of higher wind speeds, while in the uncoupled run we did not find significant change in the relative distribution. Additionally, wind speeds and VTU values (upper-troposphere warm/cold core parameter) show a significant, positive correlation in the coupled simulation both for past and future climate, while no significant correlation is found in the uncoupled run for future climate. The fact that VTU is higher in the future in the coupled run, indicates that medicanes could have more robust tropical-like characteristics in the future, and these enhanced tropical features appear to be linked to higher medicane intensities. The opposite occurs in the uncoupled configuration.

An analysis of the seasonal dependence of the effects of coupling on medicanes reveals that the largest differences in medicane intensity between the coupled and uncoupled simulations take place in summer. In the uncoupled simulation, cases of intense long-lasting summer cyclones are simulated, while this does not occur in the coupled run. Summer medicanes are nearly non-existent in observed climatologies (Miglietta *et al*., 2013; Cavicchia *et al*., 2014a), and this is better reproduced by the coupled model. We hypothesize that this might be due to a negative feedback for cyclone intensity in summer that could only act in the coupled model. This feedback is due to the shallow summer mixed-layer depth in summer in the Mediterranean Sea and the associated presence of cold water at small depths. This cold water would be upwelled to the surface in case of intensifying winds, limiting the latent heat fluxes necessary for the development of a medicane. Though the absence of intense medicanes in the coupled simulation does not allow a direct verification of this suggested mechanism, observed strong wind situations unrelated to cyclones (Berthou *et al*., 2016) demonstrate the cooling potential of strong winds over shallow mixed layer waters in summer in the Mediterranean.

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